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Freeze-Crack-Related Measurements on Platanus × acerifolia Trees

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ABSTRACT. For four consecutive winters, stem temperature, stem shrinkage, and widths of freeze cracks were measured on London plane trees, *Platanus × acerifolia*, in Urbana, Illinois. At temperatures below 0°C, trunk shrinkage and widths of freeze cracks were substantial and inversely correlated with temperature. Wood shrinkage was greater in trees with cracks than in trees without cracks. FOR. SCI. 33(1):239–244.

ADDITIONAL KEY WORDS. Frost cracks, winter injury, plane tree.

SHRINKAGE OF TREE STEMS is common under certain environmental conditions. Diurnal changes in dimension as a result of transpirational loss of water through leaves have been precisely measured (Kramer and Kozlowski 1960). Wood also can shrink as a direct result of lowered temperature (Kubler et al. 1973, Panshin and deZeeuw 1980). At temperatures above 0°C, the strain produced by dimensional changes in the wood of living trees is rarely sufficient to cause rupture. Below the freezing point, dimensional shrinkage can cause tree rupture (Kubler and Traber 1964).

Frost cracks or, more precisely, freeze cracks are radial-longitudinal separations of the wood and bark of tree stems that occur at temperatures below 0°C. Although most are formed on the tree trunk, large branches may also develop freeze cracks. Kubler (1983) offered an explanation of freeze cracks in trees based on the following general observations: (1) existing cracks widen when trunk temperatures drop below 0°C; (2) cracks close as trunk temperatures return to 0°C; (3) during cooling, but at temperatures above 0°C, dimensions of green wood remain essentially stable; and (4) below 0°C, wood freeze-shrinks progressively as temperature drops, whereby tangential freeze shrinkage exceeds radial freeze shrinkage by a factor of two, just as in the case of shrinking due to drying in air. Kubler argued that at temperatures below 0°C, shrinkage is due to a form of internal freeze-drying as moisture migrates from the cell walls to ice loci in empty cell lumens. As a result, the cellular components pull closer together; in effect, the cell walls and the stem itself shrink. This freeze-drying of the cell walls, he suggested, shrinks tree trunks in essentially the same manner as the air-drying of lumber. Freeze cracks result from excessive tangential strain, with the rupture in the radial-longitudinal plane. The objective of our field study was to determine the extent of trunk shrinkage in winter and to correlate this shrinkage with crack width and stem temperature.

MATERIALS AND METHODS

The London plane trees (*Platanus × acerifolia* [Ait.] Willd.) used in this study were selected each year from a uniform group of 38 amenity trees on the campus of the University of Illinois in Urbana-Champaign. Thirty of the trees had freeze cracks and eight did not. The trees were 20 to 24 years old and averaged 38.4 cm in diameter the first year of the study. The cracks faced all cardinal directions; 60% opened toward the southeast, south, or south-

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TABLE 1. Average freeze-crack widths at approximately 1 m height on 20 London plane trees in winter at 8:30 a.m. and 4:30 p.m.

	8:30 a.m.		4:30 p.m.		Difference*	
Date	Air temp (°C)	Crack width (mm)	Air temp (°C)	Crack width (mm)	Air temp (°C)	Crack width (mm)
Jan. 25	−13	45.9	−7	40.7	6	5.2
28	−22	50.8	−12	40.2	10	10.6
29	−14	48.7	−6	42.5	8	6.2
30	−11	43.4	−12	38.3	(1)	5.1
31	−19	47.1	−11	39.5	8	7.6
Feb. 1	−10	42.4	+1	25.4	11	17.0
5	−2	8.0	+8	0.0	10	8.0

* Temperature increase (or decrease) and crack closure.

west; 40% opened toward the west, northwest, north, northeast, or east. Cracks ranged from 1.2 to 3.0 m in vertical length.

The width of each crack was periodically measured to the nearest mm with a metric ruler at a marked point of widest gaping, usually about 1 m up the stem. Trunk diameters were measured with a steel tape (thermal expansion coefficient 15×10^{-6} mm/mm C) at the same point. Tree diameters were obtained each November at air temperatures above freezing and prior to crack opening to establish a base figure for winter shrinkage.

Trunk wood temperatures were measured during the second year with a tele-thermometer (YSI Model 42SC), utilizing a switchbox (YSI Model 4002) and stationed thermocouples (YSI Model T2600). Each thermocouple probe had a vinyl plastic tip 4.8 mm wide and 7.9 mm long with a vinyl plastic sheath 3.5 mm wide and 3 m long leading to a connector plug. A hole 6.3 mm in diameter was drilled into the trunk to a selected depth to accept the thermocouple. The hole around the lead was sealed with putty. Measurements proceeded as follows:

Year 1. Crack-width measurements were taken on 20 London plane trees on 7 days during late January and early February when daily temperatures remained below 0°C. Measurements were made at approximately 8:30 a.m. and 4:30 p.m., when cracks were at their widest and narrowest, respectively, for the day. On January 31 and February 1, measurements were made hourly from 8:15 a.m. through 5:15 p.m. Tree diameter measurements were taken on 3 mornings at 8:30 a.m.

Year 2. Measurements of the diameters of 20 trees were made on 2 dates when the air temperature was above 0°C and on 1 date in December when the air temperature at 8:30 a.m. was −18°C. At −18°C, 17 of the 20 trees had open freeze cracks that were measured at that time.

One tree with a freeze crack had six thermocouples inserted into it at a height of 1 m: four of them at depths of 7 cm, one in each cardinal direction; a fifth was inserted to the west at a depth of 10 cm; and a sixth to the north at a depth of 15 cm. On 10 days in January and February, when the mean daily air temperature was below 0°C, the trunk temperature of this tree was taken shortly after 8:00 a.m. and before 5:00 p.m. On 5 of these days, the temperature was taken at 2-hr intervals from 8:00 a.m. through 5:00 p.m.

Six thermocouples were inserted at heights of 1.0 to 1.3 m into each of two other trees with open freeze cracks throughout February. Three faced north and three faced south at depths of 5, 15, and 25 cm. On 6 days, when the mean daily air temperature was below 0°C, trunk temperatures of the two trees were taken at approximately 8:30 a.m. and 4:00 p.m.

Year 3. Diameters of 20 trees and crack widths were measured at approximately 8:30 a.m. on 2 dates when the air temperature was above 0°C and on 3 dates when the air temperature was well below freezing. Fifteen of the trees had cracks and five did not.

Year 4. Diameters of 25 trees and crack widths were measured on 1 date when the air temperature was above 0°C, and on 3 dates when the mean daily air temperature was below 0°C. Nineteen of the trees had freeze cracks and 6 did not.

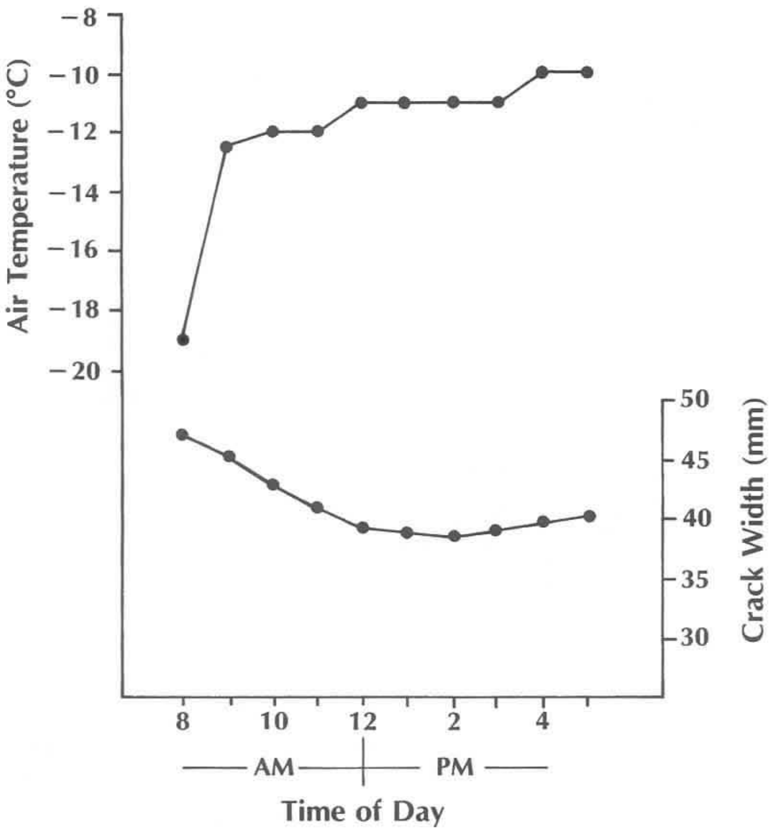

FIGURE 1. Ambient air temperature and average crack width on 20 London plane trees, January 31, Year 1.

RESULTS

The widths of freeze-crack openings were inversely related to ambient air temperatures when the mean daily temperature was below freezing. Widths at 8:30 a.m. and 4:30 p.m. for 7 days of Year 1 are presented in Table 1. The average crack widths for 8:30 a.m. were 43.6 mm for Year 2 at −18°C; 19.0 mm for Year 3 at −15°C and 43.3 mm at −21°C; 8.1 mm for Year 4 at −8°C, 12.9 mm at −12°C, and 21.8 mm at −17°C. The correlation coefficient in Year 1, when the air temperature was below −10°C, was 0.862. Combining the data from Years 2, 3, and 4 gave a coefficient of 0.618. Over the 4 years at 8:30 a.m., cracks opened 1.8 mm for each degree of temperature below 0°C. As air temperature increased during the day, crack width decreased. For each degree of increased air temperature from 8:30 a.m. to 4:30 p.m. on the 7 days reported in Table 1, a decrease in crack width of about 1 mm occurred. Hourly changes of temperature and crack width for January 31 are presented in Figure 1.

The width of freeze-crack openings correlated more closely with trunk temperature than with air temperature. The correlation coefficient between crack width and trunk temperature taken from a west-facing thermocouple inserted to a depth of 7 cm was 0.910. Stem temperature, again as shown in Figure 2, varied with air temperature, facing direction, and depth of the thermocouple. The south-facing portion gained additional heat from radiant energy and was significantly warmer during the day than were the east-, west-, and north-facing portions. The average of 5 days of temperature readings taken throughout the day at a depth of 7 cm is illustrated in Figure 3. As would be expected from the low thermal conductivity of wood, daily fluctuations in the interior of the tree were smaller than those nearer the surface (Figure 2). Given the limited field observations in this study, trunk

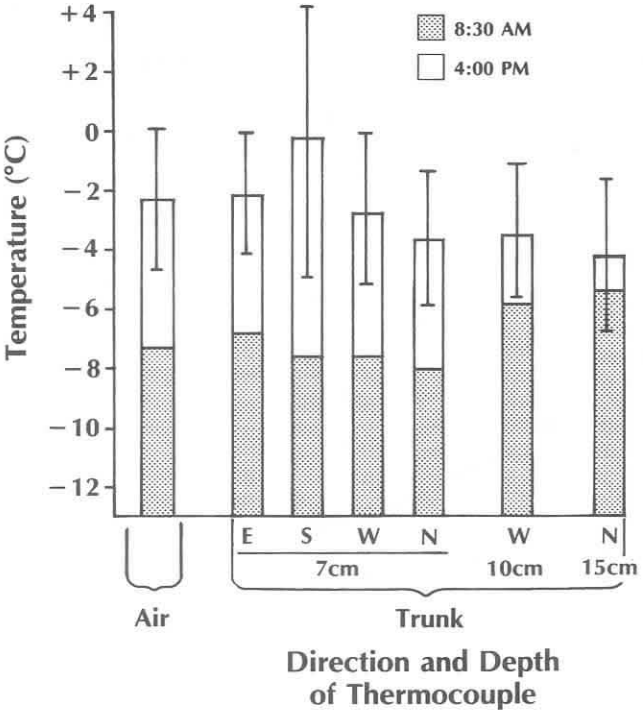

FIGURE 2. Ambient air temperature and trunk temperature in a London plane tree at approximately 8:30 a.m. and 4:00 p.m., average of ten days, Year 2. Bars indicate two standard deviations (P = 0.05).

temperatures taken at 8:30 a.m. at a depth of 7 cm appeared to be close to equilibrium with the ambient air temperature (Figures 2 and 3), trunk temperatures at depths up to 25 cm deep and taken from the east-, west-, or north-facing thermocouples differed by no more than 2°.

The shrinkage of wood in living trees exposed to daily temperatures below the freezing point is substantial. In London plane trees without freeze cracks, the cross-sectional area shrinkage was 2.62% at −18°C in Year 1 (Table 2). At a given temperature, the reduction of cross-sectional area (also circumference) of trees with freeze cracks was less than that

TABLE 2. Percent shrinkage of the cross-section area of London plane trees at approximately 1 m height in winter.

Year	Ambient air temp (°C)	Percent shrinkage and standard deviation (P = 0.05)		
		No crack*	With crack**	
		Trunk	Trunk	Wood***
2	−18	2.62 ± 0.43	2.01 ± 1.06	4.57 ± 1.65
3	−15	0.89 ± 0.33	0.25 ± 0.17	1.47 ± 0.48
	−21	2.26 ± 0.56	1.40 ± 0.59	4.06 ± 0.93
4	−8	1.35 ± 0.37	1.48 ± 0.36	2.32 ± 0.44
	−12	1.55 ± 0.48	1.44 ± 0.33	2.00 ± 0.36
	−19	1.99 ± 0.38	1.68 ± 0.66	3.11 ± 0.54

* Year 2, average of 3 trees; Year 3, average of 5 trees; Year 4, average of 6 trees.
** Year 2, average of 17 trees; Year 3, average of 15 trees; Year 4, average of 19 trees.
*** Includes bark, which is less than 3% of the total.

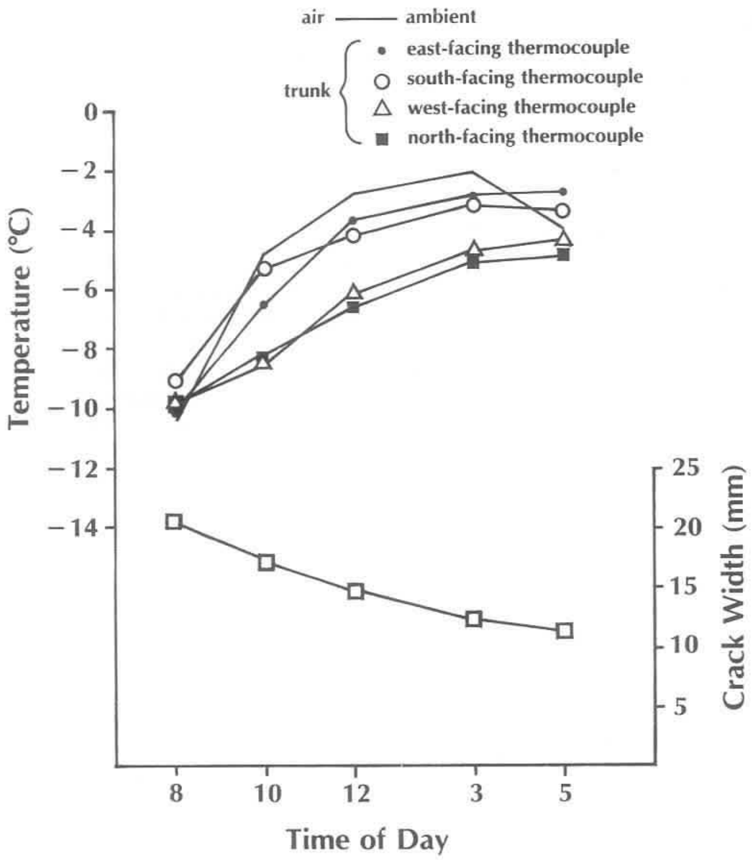

FIGURE 3. Ambient air temperature, trunk wood temperature at a depth of 7 cm, and freeze-crack width in a London plane tree, average of five days, Year 2.

of trees without cracks. When the area of the arc segment of the crack was subtracted, however, the wood shrinkage was much greater in trees with cracks (Table 2). Wood shrinkage of 4% at temperatures near −20°C was not uncommon.

The winter diurnal swelling of trees was readily measured. On a day in Year 4 (Table 2) when the air temperature was −8°C at 8:30 a.m., the circumferences of trees with cracks had increased 0.06% by 1:00 p.m. and 0.09% by 4:00 p.m., with air temperature increases of 4° and 3°C, respectively. On the same date, trees without cracks had increased in circumference 0.13% by 1:00 p.m. and 0.19% by 4:00 p.m. On another day in Year 4 when the air temperature was −12°C at 8:30 a.m., with air temperature increases of 6° and 7°C, the circumference of trees with cracks had increased 0.07% by 1:00 p.m., and 0.10% by 4:00 p.m. Trees without cracks had increased in circumference 0.17% by 1:00 p.m., and 0.30% by 4:00 p.m.

DISCUSSION

Ambient air temperatures are seldom stable; neither do they change uniformly. Cracks on London plane trees do not open immediately when the air temperature drops to 0°C. Even when surrounded by colder air, the temperature of the tree trunk hovers near the freezing point until the latent heat of fusion is released. Freeze cracks from previous years open only after the stem has cooled to a temperature below 0°C. Cracks on London plane trees in central Illinois open 24 to 48 hr after the mean daily air temperature has dropped below 0°C. The ambient air temperature at the time of opening may be −10° to −13°C (Himelick 1970). Cracks remain open as long as the mean daily temperature remains below freezing.

open, the width of a crack reflects closely the wood temperature. Cracks fully close when the mean daily air temperature is above freezing for 24 to 48 hr.

Many explanations of freeze cracks continue to be based on the theory of thermal contraction: cracks result from the rapid cooling and contraction of the bark and outer wood while the inner wood remains warm with less contraction (Kramer and Kozlowski 1960). If this theory were valid, radial, vertical cracks would occur only in the exterior rings of the bole with extensive ring shakes beneath. Although the trees studied here could not be sectioned to examine the exact penetration depth of cracks, they appeared to have a form and depth consistent with the definition of freeze cracks given by Kubler (1983) (i.e., complete arc segments reaching to the center of the tree).

The freeze-dry hypothesis that is proposed by Kubler (1983) to explain freeze crack formation in trees in winter is largely based on experimentation on wood samples in the laboratory. Our measurements of mature trees confirm that at temperatures below 0°C there is substantial trunk shrinkage. The wood shrinkage in trees with freeze cracks is greater than in trees without freeze cracks. Our temperature measurements at varying depths in the trunk establish that there is relative uniformity of wood temperatures. The temperature data do not indicate that a temperature differential between exterior wood and interior wood is a likely cause for freeze cracks. Our shrinkage and temperature measurements wholly support the freeze-crack mechanism given by Kubler (1983).

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